AUTOMATED DATA MONITORING AND ANALYSIS FOR THE ATLAS/CENTAUR LAUNCH VEHICLE

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ABSTRACT

Under contract to the NASA Marshall Space Flight Center, Lockheed Martin Astronautics, Rockwell International Space Systems and the NASA Lewis Research Center developed, implemented, and matured automated data monitoring and analysis technologies and quantified the return on investment for potential value added to next generation launch systems. The workstation-based Atlas/Centaur Automated Diagnostic System (ACADS) focused on event detection routines, rule-based and model-based expert system technologies and statistical analysis applied to data monitoring and analysis of the Centaur Pneumatics subsystem. This paper represents the role of each of these technologies in ACADS, as well as results achieved in applying these technologies to Atlas/Centaur data.

INTRODUCTION

A major cost in processing today's launch vehicles is test & checkout of propulsion systems. A significant portion of this process is consumed by manual data monitoring and analysis. In an effort to reduce launch processing costs, a select subset of measurements is evaluated in support of day-to-day operations. System engineers focus on major vehicle readiness tests for more comprehensive fault observation. This success oriented approach places at risk schedule and costs associated with recycled tests and penalties for launch delays. Automated data monitoring and analysis reverses this trend, once again allowing for a continuous and comprehensive review of vehicle performance. Detectable faults are observed at first occurrence, reducing risk to cost and schedule. Observation of incipient faults enables proactive corrective action, resulting in increased vehicle flight reliability.

The Atlas/Centaur Automated Diagnostic System (ACADS) is operational today at Space Launch Complex (SLC) 36. Under contract to the NASA Marshall Space Flight Center, the ACADS program developed and matured real-time automated data monitoring and analysis technologies for application on next generation launch systems. These technologies were enabled by and hosted on the Lockheed Martin Astronautics developed Automated Data Monitoring System (ADMS) at SLC-36. A combination of commercial-of-the-shelf tools and custom analysis routines were integrated to perform continuous and comprehensive monitoring of launch system data. Benefits of this technology are being realized in the form of reduced engineering support costs and accelerated fault observation.

RESULTS AND DISCUSSION

OVERVIEW

The objective of the Atlas/Centaur Automated Diagnostic System was to develop, implement, and mature automated data monitoring and analysis technologies while measuring the value added to next generation launch systems. Continuous and comprehensive data monitoring and analysis have reduced recurring operations costs while increasing vehicle availability and flight reliability. Existing data monitoring and analysis requirements were defined in terms of the expected behavior of vehicle subsystems under various vehicle configurations and operational states. ACADS satisfied these requirements by combining event detection routines with statistical, rule-based, and model-based analyses to assess system behavior.

ACADS employs the G2 expert system shell by Gensym Corporation for its user interface and to perform the statistical analysis and rule-based and model-based reasoning. The event detection routines have been coded in C, which is readily callable from G2.

USER INTERFACE

Although the Centaur Pneumatics Automated Diagnostic System application operates autonomously, a graphical user interface was developed to support subsystem component characterization, notification of the system engineer of potential anomalous conditions, and rapid manual verification of the anomaly. The ACADS application typically appears as an icon in the corner of the system engineer's ADMS-based electronic stripchart display. When ACADS detects a potential anomaly, a flag is displayed on the screen. The end-user can then bring ACADS to the front to learn more about the reasoning behind the flag. The primary ACADS Centaur Pneumatics application display is a top level schematic diagram (Figure 1). Subsystem and component level displays can be opened by a point-n-click with the mouse. Helium Storage, Purge Bottle, LH2 and LO2 Tank Pressurization and Intermediate Bulkhead graphical displays are available as well as a variety of graphs and charts to support manual observation of system behavior. In addition to the front end potential anomaly flag, notices and a logbook are used to alert the end-user of events or potential anomalies that require attention.

CENTAUR PNEUMATICS OVERVIEW

Previous studies have identified the Centaur Pneumatic system as a prime candidate for automated data monitoring and analysis technologies.[1] To facilitate discussion of the application of these technologies to the Atlas/Centaur vehicle, brief descriptions of the Centaur Pneumatic subsystem and the pre-launch helium supply bottle charging process are given below.

The Centaur Pneumatics system controls Centaur propellant tank ullage pressure and continuously furnishes regulated pressure for Centaur engine controls, reaction control, and purge systems. The system also includes a purge bottle mounted on the Interstage Adapter that provides helium blocking purges to the Centaur engines during flight through the atmosphere, and supplies helium for pressurizing the Liquid Hydrogen (LH2) tank before Atlas/Centaur staging.

The helium used by the pneumatic system is contained in 4000 psig composite storage bottles. The high pressure helium from the bottles is regulated to 450 psig (nominal) for operation of engine controls, pressurization of the RCS propellant tank, and pressurization of purge lines. Helium is added to the tanks to raise pressure prior to engine starts and to maintain LO2 tank pressure during engine firings. Gaseous hydrogen, supplied by the main engines, is used to maintain LH2 tank pressure during engine burns. For helium pressurization in both tanks and for GH2 pressurization in the LH2 tank, the flight control system senses tank ullage pressures, via transducers, and actuates pressurization valve modules to

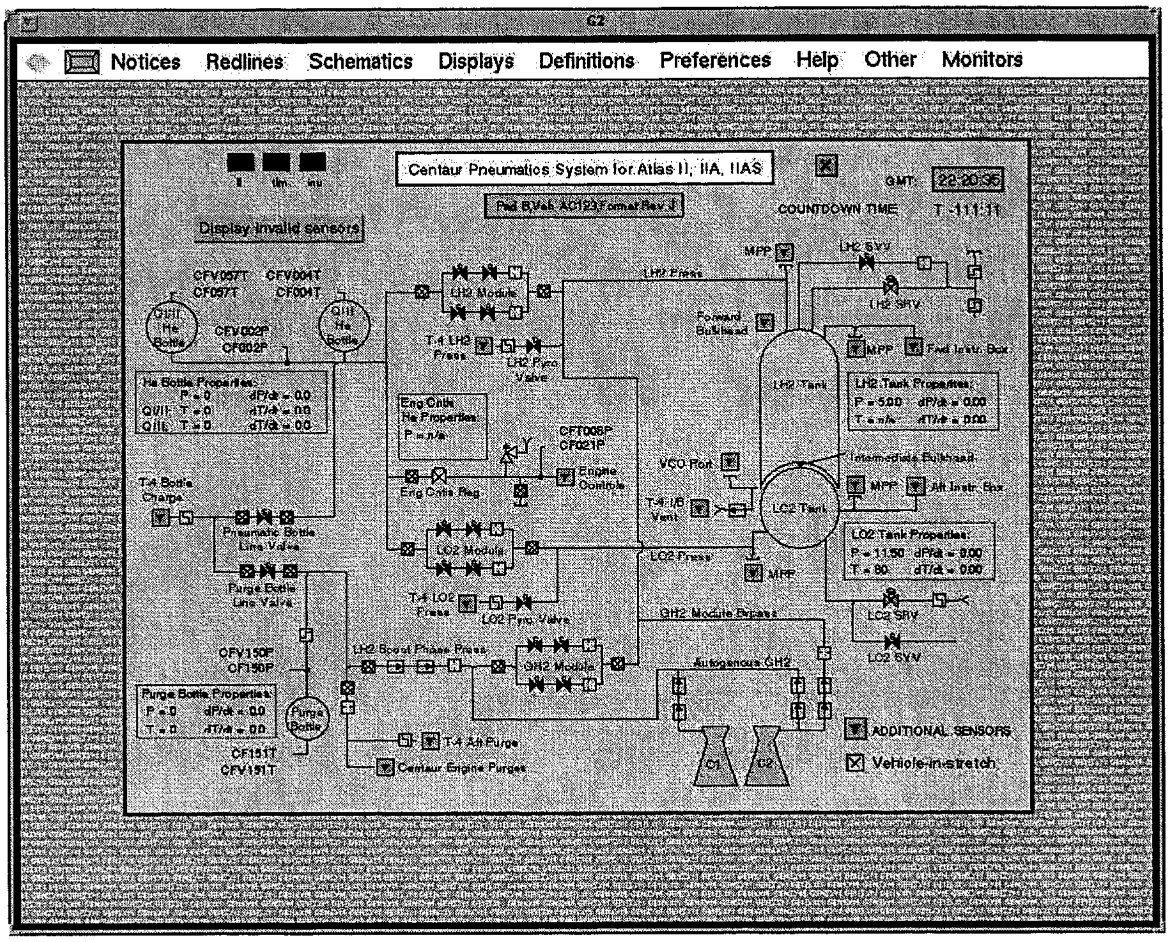

Figure 1: Centaur Pneumatics Application Primary User Interface

allow high pressure gas flow, through orifices, into the tanks. This closed loop control system provides the required net positive suction pressure for all engine operations and the pressures required for tank and intermediate bulkhead structural integrity during all phases of flight.

The nominal Centaur helium storage bottle and purge bottle charge sequence for an Atlas II Wet Dress Rehearsal (WDR) — a major test designed to simulate an actual launch countdown by fully tanking the vehicle with propellants — or launch countdown at SLC-36A or SLC-36B is: 1) simultaneously pressurize the helium and purge bottles to 800 to 1000 psig, then hold; 2) vent the purge bottle to remove GN2 (purge bottle blowdown); 3) continue helium bottle pressurization, but not the purge bottle pressurization, until a 3000 psig maximum precharge pressure (personnel safety limit) is achieved, then hold; 4) as personnel are being cleared from the complex, pressurize the purge bottle to approximately 3000 psig, matching the helium storage bottle precharge pressure; 5) after personnel are cleared from the complex, continue simultaneous pressurization of helium storage and purge bottles to 4000 psig maximum flight pressure; 6) maintain bottle pressure at the targeted flight pressure as bottles cooldown from initial charging; 7) verify that helium storage bottles have achieved flight mass (pressure/temperature combination in specified limits) before commencing terminal countdown; and 8) at T-90 seconds, secure helium and purge bottle charging.

Atlas/Centaur vehicles (given designations such as AC-111) are launched from two launch complexes, SLC-36A and SLC-36B, at Cape Canaveral Air Station. Due to facility differences, the charge rate capability on B-Pad is approximately twice that of A-Pad. There are additional variables which can affect the charge process. For example, the helium bottles may be insulated or un-insulated to varying degrees. Finally, although the charge process is typically automated, manual operation introduces additional variation in the charging pressure and temperature data signatures.[2]

EVENT DETECTION

The most critical element to increasing vehicle flight reliability is the continuous and comprehensive monitoring of all vehicle data. Every event must be detected and analyzed to determine if it was expected, and if so, if it was nominal. Given the large amount of data that must be analyzed, it is typically not feasible to reason on each data sample. To function effectively in a time indeterminate pre-flight environment and to minimize demands on the system engineers, automated analysis processes must be event-driven. Specific system phenomena can be identified by characteristic signatures of associated vehicle measurements. Once the events in the data stream have been identified, an expert system or statistical routines can be used to distinguish and resolve expected and unexpected phenomena. Out-of-family behavior can be flagged and instrumentation problems can be distinguished from other hardware anomalies.

The NASA Lewis Research Center has developed and demonstrated event detection algorithms for post-test analysis of Space Shuttle Main Engine performance parameters and Atlas/Centaur pneumatic and electrical system data.[3,4] In order to accommodate the ACADS objective of real-time automated diagnostics for launch vehicle monitoring, five event detection routines, suitable for real-time analysis, were implemented: spike, limit exceedence, redundant channel check, noise and drift/level-shift.

The post-test spike, limit exceedence, redundant channel check and noise routines were easily adapted for real-time analysis. For both real-time and post-test analysis, these routines examine small windows of data at a time, and do not rely on having the entire parameter history available at the start of the analysis. The post-test drift/level-shift algorithm requires the entire data set to be available prior to execution. Therefore, a new drift/level-shift routine was developed for real-time analysis.

Because changes in the spike, limit exceedence, redundant channel check and noise event detection logic were minimal, this study focused on the performance of the real-time drift/level-shift routine. To detect drifts and level shifts within a data stream, the routine takes as input several user-selectable parameters based on the typical noise exhibited by the parameter in question and the minimum event magnitude that is desired. The routine was tested against data from eight WDRs, four from SLC-36B (AC-111, AC-113, AC-115, and AC-117) and four from SLC-36A (AC-118, AC-119, AC-120, and AC-122). Specifically, the various stages associated with charging the Centaur helium and purge bottles from 0 psig to 4000 psig were monitored for drifts. The same thresholds were used to monitor all pressures associated with the charge process on all SLC-36B WDRs. A slightly modified set of thresholds was used for all SLC-36A WDRs. The minor changes reflected a characteristically slower charge rate on SLC-36A. Excellent results were obtained on all WDRs; Figure 2 shows the positive drifts detected by the drift/level-shift event detection routine in the helium bottle pressure on AC-117 during the third step of the bottle charge process, as described above.

The detection of events enables the automated assessment of system condition. Limit exceedances and redundant channel violations were used extensively to perform the rule-based analysis. The drifts in the helium and purge bottle pressures, together with information on the position of various valves, were used in rules which identify the current stage of the bottle charge sequence; this partitioning was required to perform the statistical analysis. The drifts were further used to determine if the observed charge rates were statistically 'within family'. This analysis is described in a subsequent section.

RULE-BASED ANALYSIS

The detection of events, even simple events such as limit exceedences and redundant channel discrepancies, permits an effective automated analysis of launch system readiness. Commercial-off-the-shelf

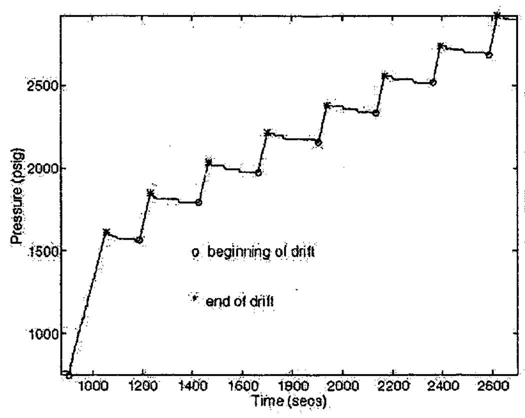

Figure 2: Helium Bottle Pressure Profile During Third Stage of Charge Process

expert system shells, such as G2, provide a quick and cost-effective mechanism for drawing inferences based on the events extracted from the vehicle data. Several rule-based modules have been implemented in ACADS. These include state/configuration determination and sensor validation modules, and watchdog and system test monitors as described below.

State/Configuration Determination

The state of the launch system, the configuration of the vehicle, and the process or procedure currently being executed must be determined in order to successfully reason about the values being measured by ACADS. While some states or processes can be determined by simply measuring a value on the data bus, many times this information must be inferred from a combination of measurements. While the goal is to operate fully autonomously, some input may be required from the end-user until instrumentation can be put in place to provide the information. State/configuration determination is implemented on ACADS. Furthermore, ACADS notifies the operator if readings and/or inputs provide conflicting information regarding the system state.

Sensor Validation

Valid sensor data is absolutely essential to the successful operation of any autonomous data monitoring and analysis system. Instrumentation problems account for an average of 25% of all observed anomalous data. Determination of sensor validity can be a very complex process. In the most elementary situation, redundant sensors provide a means for verifying the accuracy of a measurement. Even in this situation, calibration errors can be enough to generate potential anomaly flags. More difficulty results from the fact that various sensors are powered by different busses on the vehicle. Some sensors are not in range unless the vehicle is in a certain state. Some values have to be ignored when certain subsystem level tests are being executed. Nominal values for different measurements vary from vehicle to vehicle, and state to state. ACADS must address every one of these factors before reasoning on any of the data. It does not take many false alarms to significantly reduce the confidence of the end-user system engineer.

ACADS performs state/configuration dependent reasonableness checks for all monitored sensors, performs redundant channel comparisons when applicable, verifies relevant data acquisition units are operational, and includes logic to avoid anomaly flags during sensor calibration. Day-to-day operation of ACADS significantly increases the probability that instrumentation problems will be observed and corrected before they impact major test operations. An example of this occurred in the early morning preceding the AC-125 WDR. The Centaur Pneumatics application reported probable data loss anomalies, as well as apparent LH2 and LO2 tank standby pressure limit violations. Subsequent data playback showed that there was an approximate 300 millisecond data dropout at this time affecting both of these sensors, and other landline sensors as well. A general instrumentation problem was suspected and the anomaly information was forwarded to landline engineering for evaluation long before it could impact a major test operation.

Watchdog Monitors

Watchdog monitors are operational 24 hours a day while a vehicle is on the pad. These rule-based routines monitor key measurements for any possible vehicle state or configuration. This is perhaps the most important element of ACADS, as it is here that detectable faults not under manual observation could most likely go un-noticed until a major event test is impacted.

The watchdog monitor measures and reasons on pressure, temperature, current, and displacement values for Centaur Pneumatics subsystems during various vehicle configurations and processing states. Subsystems include propellant tanks, intermediate bulkhead, helium storage and purge bottles, the engine controls regulator, forward bulkhead cavity and valves. Vehicle configurations and states include day-to-day operations, subsystem tests, vehicle level initial electrical readiness tests, simulated flight tests, wet dress rehearsal, comprehensive electrical readiness tests, and launch.

During the AC-120 launch countdown, ACADS issued a caution message that the Centaur LO2 tank pressure had exceeded the 13.4 psig limit with an increasing trend due to the helium inflow from system purges. The blockhouse Centaur Pneumatics panel operator was notified, and LO2 tank pressure was vented to a nominal level. ACADS provided the only real-time alert due to the fact that the blockhouse meter displays only the landline measurement, whereas ACADS monitors 5 different measurements.

During the AC-121 launch countdown, ACADS issued a warning message that airborne helium purge bottle pressure had exceeded the 3,000 psig intermediate pressurization level established as a safety limit for personnel working inside the complex. ACADS provided the only real-time alert due to the fact that blockhouse panels were reading only the landline measurements and the airborne measurement exceedences were too short in duration to be noticed on real-time digital displays.[5]

Test Support Monitors

While watchdog monitors evaluate subsystem operation 24 hours a day, test support monitors are operational only in support of specific system tests. While the data for a system under test is being closely monitored by conventional mechanisms (e.g. manual observation of a stripchart display), ACADS provides a second "set of eyes" as well as a greater level of fidelity in data observation and analysis.

A number of subsystem tests require the Centaur Pneumatic system to be up and operational. Whenever a helium bottle is charged, a test support monitor is launched to verify nominal operation of the helium bottle charging process. Further analysis of this charge process is performed by the statistical and model-based routines. These test support monitor functions include helium bottle charge test, helium bottle lockup test, valve module tank pressure rise test, purge bottle blowdown test, self-regulating vent valve test, intermediate bulkhead vacuum test, and LH2 solenoid vent valve test.

STATISTICAL ANALYSIS

The drifts identified by the real-time drift/level-shift algorithm described earlier were further analyzed to determine if the helium and purge bottle charge processes could be statistically characterized. Such a characterization would allow warnings to be issued in the event that 'out-of-family' behavior was observed. Out-of-family behavior may, for example, be indicative of a system leak. The analysis was initially performed on the SLC-36B WDRs; a range of possible bottle charge scenarios was represented by these data sets. AC-111 was not insulated for WDR, while AC-113, AC-115 and AC-117 were insulated.

For the AC-113 WDR, the thermal blanket completely encapsulated the helium bottles; this was not the case with the other insulated WDRs. Finally, AC-113 experienced periods of manual bottle charge. Auto-bottle charge was in effect for the other three WDRs.

Despite these differences, a clear correlation emerged when the charge rate for each step (upward drift) of the charging process was considered as a function of the average bottle pressure during that step. For this particular correlation, only the third stage of the charging process, shown in Figure 2, was considered. The correlation is illustrated for the SLC-36B WDRs in Figure 3 and for the SLC-36A WDRs in Figure 4. The center curves represent the results of a linear fit after a natural log transformation (Figure 3) or quadratic fit (Figure 4) of the (average bottle pressure, charge rate) data pairs. The outer curves represent approximately the 99.5% confidence intervals.[6] The asterisks represent the individual data pairs used to generate each fit. The calculations which yield the average bottle pressure and charge rate (slope) during each drift can easily be computed in real-time following the identification of a drift. The threshold computations based on the average bottle pressure are also not computationally intensive.

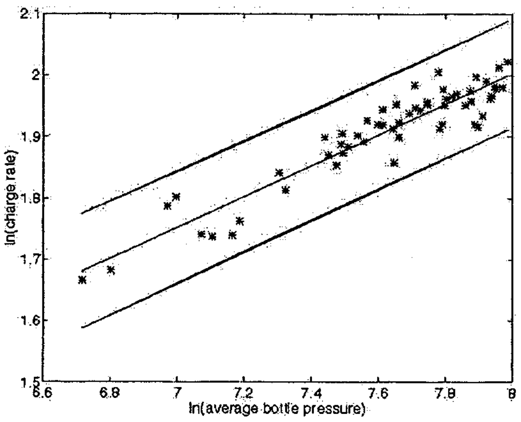

Figure 3: Correlations & Confidence Intervals For SLC-36B

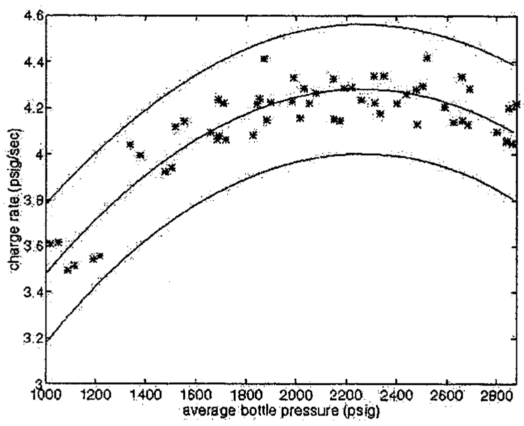

Figure 4: Correlations & Confidence Intervals For SLC-36A

As can be seen from Figure 5, the SLC-36B and SLC-36A data pairs form distinct families. Similar results were obtained for the purge bottles. Statistical correlations that detect out-of-family behavior have been integrated into ACADS.

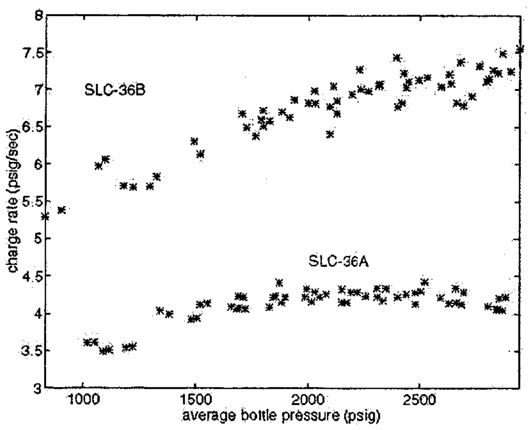

Figure 5: A-Pad & B-Pad Distinct Families

MODEL-BASED ANALYSIS

Model-based reasoning adds substantial diagnostic information when the number of real-time measurements is limited and the parameters not measured can be calculated. Models must accurately predict those parameters that are measured in order to have confidence in the other parameters that are calculated. Incorporation of model-based reasoning algorithms into the expert system can provide increased visibility and conviction in system performance and health monitoring assessments.

The system selected for modelling was the Centaur pneumatic subsystem Helium bottle pre-launch charge and vent system. The difficulty with current real-time monitoring is that only a few measurements are available for diagnostics. The model defines calculated relationships between variables and the behavior of variables that can aid in controlling the charge and vent operations and in verifying helium supply system health. Therefore, this system was ideal to demonstrate first principles math modeling.

The approach was to collect the relevant thermodynamic and fluid dynamic equations and physical constants to accurately model the Centaur pneumatic system. The pneumatic system utilizes a compressible gas with relatively low viscosity and density; therefore, the gas flow can be either sonic or subsonic. Because fluid inertia is usually neglected in pneumatic analysis, the simplest model is a polytropic resistance-capacitance model for each He storage bottle. The theory of gas flow through an orifice provides the basis for modeling all pneumatic components. The model utilizes Newton's laws, conservation of mass, the isentropic process formula, and the perfect gas law, and assumes that viscosity effects are negligible and that local heat transfer is small.

Pressure, temperature, volume, compressibility factor and mass are functionally related through the perfect gas law. The compressibility factor for the He gas in each bottle is computed using the Beattie-Bridgeman equation and the Newton-Raphson iterative method. Each bottle's He mass is computed using the perfect gas law. The simulation model computes the pressure, temperature, accumulated mass, mass flow rate, and compressibility factor of the He in each bottle for each phase.

The model has been successfully tested on WDRs for AC-122, AC-123, and AC-125 and is now considered operational. Figure 6 illustrates comparisons between actual and predicted values for the helium storage and purge bottles during the charge from 3000 to 4000 psig. Calculated mass values are also displayed. The simulated pressures and temperatures show good agreement with the actual nominal WDR data.

COST/BENEFIT

The Atlas/Centaur Automated Diagnostic System Centaur Pneumatics application is operational today at Space Launch Complex 36. ACADS championed technologies have demonstrated a 90% reduction in routine data monitoring and analysis tasks, enabling a 15% reduction in recurring labor costs. Fault detection has been accelerated 30% through automated observation of detectable faults at first occurrence.

ACADS promises significant life cycle cost reductions when analysis of results to date is applied to historical launch system operations and flight data. Continuous and comprehensive automated monitoring and analysis of launch system data would have eliminated in-flight failures which resulted from anomalies that were detectable but not observed during pre-flight operations. Had this failure category been eliminated, demonstrated flight reliability would have been 2.5% higher! Observation of detectable faults at first occurrence also allows for proactive scheduling of repairs, reduced recurring operations costs and protection of schedule.

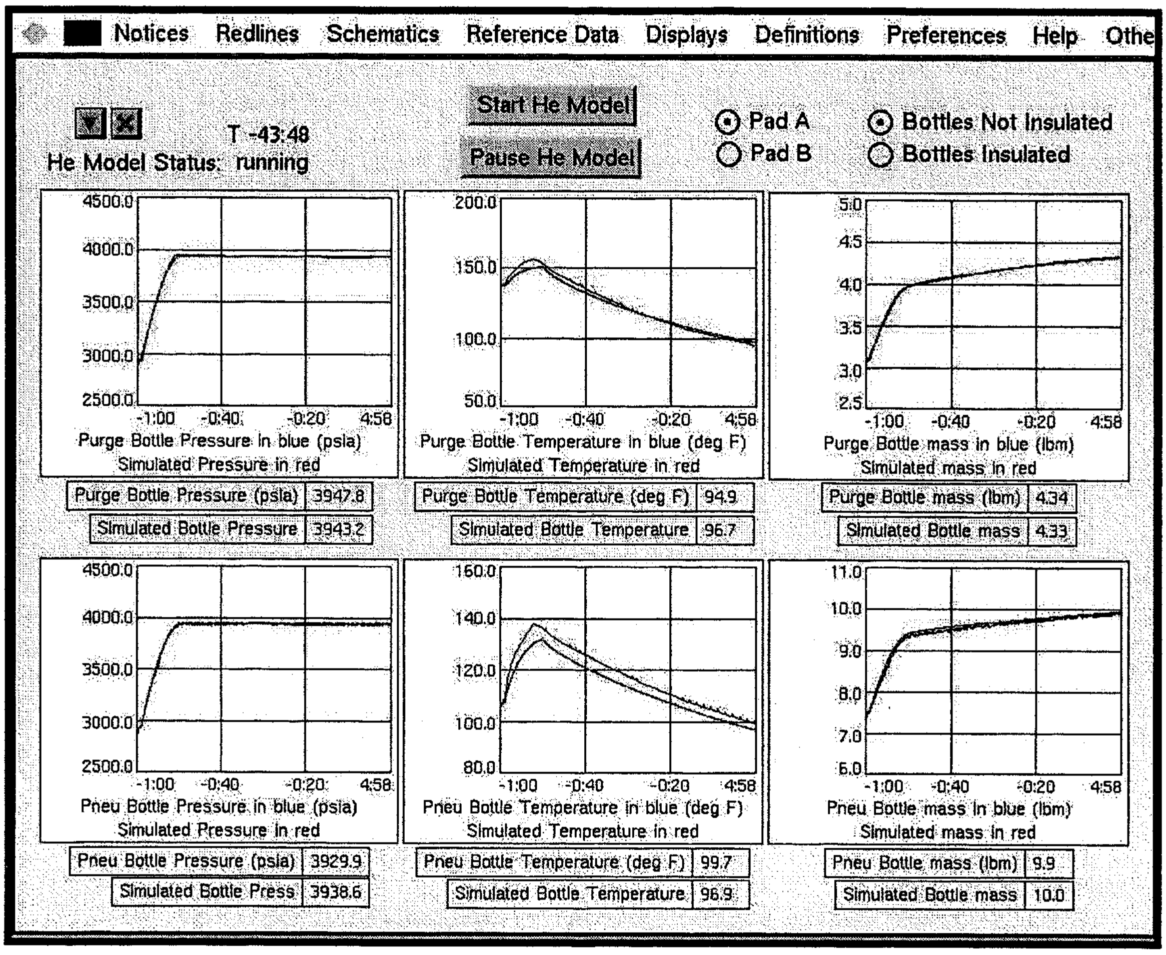

Figure 6: Helium Bottle Charge Model User Interface

ACADS technologies have proven their value added and are ready for implementation on other existing and future launch systems. Net Present Value analysis on Expendable Launch Systems concludes that automated data monitoring and analysis technologies provide up to $68 Million in value added. Applying ACADS technologies to a Shuttle class launch system reaches the break-even point after an estimated 4 months of pre-flight operations. Estimated value added ranges from $75 Million over 6 years of nominal operations to $1.5 Billion if ACADS technologies observe one detectable fault during pre-flight operations that would have otherwise gone undetected and resulted in loss of vehicle.

SUMMARY AND CONCLUSIONS

Cost reductions through automated data monitoring and analysis were measured in terms of direct reductions in recurring labor costs, labor hours required to perform data monitoring and analysis, increased engineering productivity (freeing system engineers from mundane and repetitive review tasks), accelerated anomaly resolution, and incipient fault detection in the pre-flight operational environment.

Through ACADS and other coordinated research & development efforts, several automated data monitoring and analysis technologies have been applied to the Atlas/Centaur vehicle. These include event detection algorithms combined with rule-based and first-principles model-based reasoning and statistical analysis. These technologies have been successfully tested on pre-flight data during several missions and are now operational. ACADS has confirmed that the system was operating nominally and has alerted system engineers to anomalous operation, sometimes well in advance of the traditional manual processes. These demonstrated technologies are critical in moving towards the goal of continuous and comprehensive monitoring of all launch system data.

ACKNOWLEDGMENTS AND REFERENCES

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